SCENARIO CP:
ASSESSMENT OF THE CONSEQUENCES OF THE RADIOACTIVE CONTAMINATION OF THE CHERNOBYL NUCLEAR POWER PLANT COOLING POND

ABSTRACT

The “Cooling Pond” Scenario is based on data for contamination of various aquatic media and biota due to fallout of radionuclides into the cooling pond of the Chernobyl Nuclear Power Plant. The Scenario is designed to test models and model predictions for radioactive contamination of aquatic ecosystems. Input data provided for the “Cooling Pond” Scenario include both the characteristics of the cooling pond ecosystem (hydrological, hydrochemical, and hydrobiological conditions) and estimates of the amounts of ^{137}Cs in the cooling pond as of 30 May 1986. Two sets of test data are available for comparison with model predictions:

1. Measurements of ^{137}Cs activities in the cooling pond water, in the layers of sediment, and in the fish at various time points following the accident.
2. Estimates based on measurements, including dose and risk estimates for aquatic biota and for humans consuming contaminated biota.

Important parameters to be considered in this modeling exercise include the following: sedimentation and resuspension rates; the ratio of ^{137}Cs activities in the dissolved form and on suspended matter; the biological removal rate of ^{137}Cs; and ^{137}Cs bioassimilation with food. A detailed description of the “Cooling Pond” Scenario is provided, along with tables of input data and test data.

INTRODUCTION

The aftermath of the 1986 Chernobyl accident provided a unique opportunity to collect data sets specifically for the purpose of model testing (Hoffman et al., 1996). Contamination of different aquatic media and biota due to fallout of radionuclides into a body of water – the “Cooling Pond” Scenario (Scenario CP) – is one of three major test scenarios presented by the Post-Chernobyl Data Working Group of BIOMOVS II (Biospheric Model Validation Study, Phase II) for testing models at the process level (BIOMOVS II, 1996; Kryshev et al., 1996; 1999). Scenario CP provides an opportunity to test models for radioactive contamination of aquatic ecosystems. The scenario is based on data from the Chernobyl Nuclear Power Plant (NPP) cooling pond, which was contaminated in 1986 as a result of the accident at Unit 4 of the power plant. As one of the most heavily contaminated water bodies in the world, the cooling pond provides a suitable model for studying the dynamic processes of radionuclide migration and accumulation in closed aquatic systems (Kryshev, 1992; 1995).

Scenario CP is designed for two types of calculations. (1) Model predictions of the dynamics of ecosystem contamination with ^{137}Cs can be tested using the existing database of ^{137}Cs concentrations in water, sediments, and biota. This long-lived, biologically active radionuclide determines the radioecological consequences of the Chernobyl accident for the cooling pond over long time periods. (2) Dose and risk assessment calculations based on the input data, for aquatic biota and for humans, can be compared with estimates based on the available measurements. Of particular interest is the assessment of doses received in the first two years after the accident. During this period a wide set of radionuclides contributed to the cooling pond contamination; taken together, their contribution to the total dose received by biota and humans was greater than that from cesium isotopes alone.

The input data presented in Scenario CP include both characteristics of the cooling pond ecosystem and estimates of the amounts of different radionuclides in the Chernobyl cooling pond as of 30 May 1986. Input data include measured concentrations of the most important accidental radionuclides (except ^{137}Cs) in water, sediments, and biota for several years after the accident. Geometric factors for aquatic organisms, which are important for dose calculations, are included in the input information. Concentrations of ^{137}Cs in the components of the cooling pond ecosystem are provided in the test data for comparisons with values predicted from the input data alone.

A detailed description of the "Cooling Pond" Scenario is provided below, along with a description of the types of test data available. The scenario description is followed by tables of information to be used as input data and tables of test data, including the actual measurements or estimates of dose and risk based on measurements, for comparison with model predictions. Additional information, including the results of the original BIOMOVS II model testing exercise, has been reported by Kryshev et al. (1996; 1999) and BIOMOVS II (1996).

DESCRIPTION OF THE "COOLING POND" SCENARIO

Background

The Chernobyl cooling pond provides a suitable scenario for studying the dynamic processes of radionuclide migration and accumulation in closed aquatic systems. Dynamic processes worthy of detailed investigation include (1) ^{137}Cs accumulation in different trophic levels, (2) the accumulation and removal of ^{137}Cs from fish flesh, and (3) the dependence on size of the accumulation of ^{137}Cs by various species of fish. Of additional interest is the unique temperature distribution structure of the cooling pond.

The fish in the cooling pond are assumed to have a general tendency to migrate toward regions of warmer water. Nevertheless, data confirming this assumption are not available for the cooling pond itself, and the actual habitat utilization of the fish is unknown. Quantitative data on the mortality of aquatic organisms are not available. For bottom-feeding species of fish, the age class distribution has been determined, with the smallest class being that from the 1986 generation. The available biological information indicates the possibility that fish of the 1986 generation may have been killed by the accident. Prior to the accident, the heated waters of the pond were used for commercial fishing.

Except for the year 1986, the horizontal distribution of ^{137}Cs throughout the cooling pond has been nearly uniform. The vertical profile of ^{137}Cs concentration in water was not uniform near the bottom. Sediment concentrations of ^{137}Cs are highest in the northwestern part of the pond and in deep water troughs.

Primary contamination of the cooling pond by ^{137}Cs as a result of the Chernobyl accident was due mainly to atmospheric fallout in April and May of 1986. Sources of secondary contamination of the cooling pond included wash-off from the catchment area during snow melting and rainfall, washout of ^{137}Cs from the flood plain, wind resuspension and deposition of radioactive aerosols, and direct discharge of ^{137}Cs into the cooling pond from liquid effluents. The total contribution of these secondary sources of contamination does not exceed 20% of the total amount of ^{137}Cs that entered the cooling pond from all sources. Atmospheric deposition made up at least 80% of the total inventory (Chernobyl Symposium, 1988; 1989). Furthermore, measures intended to decontaminate the terrain surrounding the cooling pond were observed to have had only a marginal effect on the inventory and on movement of radionuclides initially contributed by primary and secondary sources.

In the early period of radioactive contamination (April – May 1986), 90 – 98% of the total radioactivity of the soils and bottom sediments of the close-in zone of the Chernobyl NPP consisted of deposited fuel components. Hot aerosol particles were represented primarily by particles ranging in size from a few microns to hundreds of microns. For the bottom sediments, the geometric mean of the particle size was 14 microns (geometric standard deviation = 8). A major fraction of the ^{137}Cs in the water was in the form of suspended matter. In May 1986, up to 90% of the water activity was present in the suspended matter. Later on, as the suspended particles settled down to the sediments, the portion of the activity in the suspended matter decreased. In 1989-1990, suspended ^{137}Cs represented 10 – 40% of the dissolved fraction in water. After the accident, transformation of physical-chemical forms resulted in the destruction of "hot" fuel particles. In this case, a shift to more mobile forms was observed, and an increase in the migration capacity of ^{137}Cs was noted. However, transformation of physical-chemical forms of ^{137}Cs in the cooling pond is not the subject of most interest within the framework of this Scenario.

Input Information

The Chernobyl NPP is located in the eastern part of the Polesye region on the bank of the Pripyat River, which flows down to the Kiev reservoir. Water is supplied to the Chernobyl NPP from a cooling pond, which is located southeast of the plant site. The cooling pond was made by cutting off part of the river flood plain with a dam, and resembles an oval in shape (Figure 1). There is a water intake canal in the western part of the pond and a water discharge canal in the southern part. Hydrological, hydrochemical, and hydrobiological characteristics of the cooling pond are summarized below (Kaftannikova et al., 1987; Protasov et al., 1991).

Hydrological and Hydrochemical Conditions

The cooling pond has an area of 22 km^2 and a volume of 1.5 x 10^8 m^3 (Table 1). The average width is 2 km, the length 11.4 km, and the average depth 6.6 m. In some areas of the cooling pond there are a number of deep water pits with a depth of >10 m; the maximum depth is 20 m. About 28% of the pond water is contained in these deep water pits. Three main sediment types are present over the entire area of the pond: loamy sand (9 km^2), sand and silted sand (7 km^2), and silt (6 km^2). The sedimentation rate in shallow places is 0.4 to 2.0 cm y^{-1}, and in deep places it is 4.1 to 12.4 cm y^{-1} (Table 2). The top 10-cm layer of silts in the deep water pits has a high porosity and a density of 0.1-0.2 g cm^{-3}.

The cooling pond has no proper outflow. However, its waters reach the Pripyat River by filtration through a dam with a discharge flow of 1.2×10^5 m^3 y^{-1}.

The thermal regime of the pond (Table 3) is strongly influenced by the release of heated waters; their discharge flow was 206 m^3 s^{-1} in 1985. The waters of the cooling pond can be divided into three types: heated waters (the upper layers to a depth of 4 m), waters cooled by mixing, and cold waters in the deep water pits. Under no-wind conditions in summer, waters with a temperature greater than 28°C spread out over the upper 4-m layer to areas 6 – 11 km from the discharge canal and cover about 8.6 ± 4.4 km^2 of the pond. In effect, the strip of land that runs through the middle of the cooling pond acts as a dam, separating the heated waters from the cooler waters.

The speed of water circulation is 2 – 5 cm s^{-1} (average, 2.6 cm s^{-1}). The transfer of water from the discharge canal to the water intake canal takes about 8 days. Water losses from the cooling pond by evaporation and filtration are compensated for from the Pripyat River, using a water-pumping station located on the river bank.

The water of the cooling pond is moderately mineralized (260 – 430 mg L^{-1}) and hard (2.50 – 4.35 mg equivalent per liter; Table 4). The average concentration of potassium in the cooling pond water is 4 mg L^{-1}. Oxygen deficit is characteristic of both near-bottom and surface layers, particularly in the summer when there is a high content of organic matter. With respect to the content of biogenic and organic matter, the pond can be classified as slightly or moderately polluted, and with respect to ammonia nitrogen, as heavily polluted. Transparency of the water is 1.2 – 1.3 m in autumn and 0.6 m in summer. The content of suspended material is 10 – 30 g m^{-3}, the organic component being 40 – 50% of the total suspended matter in spring and autumn and 80 – 90% in summer (Table 5). The naturally occurring concentration of suspended material in the water is about 10 g m^{-3} (for no-wind conditions). When all four units at Chernobyl were running, operation of circulation pumps would lead to an increase in the concentration of suspended material in the cooling pond water by 15 – 20 g m^{-3}, with maximum values up to 25-30 g m^{-3}.

The Chernobyl NPP did not operate from May to September 1986, following the accident. Operation of Units 1-3 of the Chernobyl NPP was later resumed: Unit 1, in October 1986; Unit 2, in November 1986; and Unit 3, in December 1987. Pre-Chernobyl data for ^{137}Cs concentrations in the cooling pond ecosytem are given in Table 6 (Kryshev, 1992).

Hydrobiological Conditions

The pond serves as the habitat for more than 500 species and taxa of algae, over 200 species of invertebrates, and over 20 fish species, which include both nonpredators and predators. The average biomasses of different types of aquatic organisms in the cooling pond are presented in

Table 7. The most typical and widespread species of aquatic organisms with a sufficiently representative number of samples (as a rule, not fewer than 20) were used for analysis and include the following.

Aquatic plants:

- fennel-leaved pondweed (*Potamogeton pectinatus*)
- clasping-leaved pondweed (*Potamogeton perfoliatus*)
- spiked water milfoil (*Myriophyllum spicatum*)
- dark-green hornwort (*Ceratophyllum spicatum*)
- green filamentous alga (*Cladophora glomerata* Keutz)

Mollusks:

- *Dreissena bugensis*
- *Anadonta piscinalis*
- *Viviparus viviparus*
- Bivalves of the Unionidae family (*Unio pictorum*, *Unio timidus* Phill, and *Unio crassum* Phill)

Fish (Nonpredators):

- common bream (*Abramis brama*)
- silver bream (*Blicca bjoerkna*)
- roach (*Rutilus rutilus*)
- carp (*Cyprinus carpio*)
- goldfish (*Carassius auratus gibelio*)
- silver carp (*Hypophthalmichthys molitrix*)
- goby (*Neogobius*)

Fish (Predators):

- pike (*Esox lucius*)
- perch (*Perca fluviatilus*)
- pike-perch (*Stizostedion lucioperca*)

The age structure of the fish population (percentage in the population) in the cooling pond prior to the accident was determined for pike-perch: age 0-1 y, 13%; 1-2 y, 17%; 2-3y, 36%; 3-4 y, 30%; older than 4 y, 4%.

For calculation of internal exposure for aquatic organisms, radionuclides were assumed to be distributed uniformly in the organisms; in each case the tissue density was assumed to be unity (Woodhead, 1976; 1979; Kryshev and Sazykina, 1986). The shape and size of an organism (generally in terms of a mean geometrical factor, g) must be considered for calculation of the absorbed dose rate from gamma radiation (Woodhead, 1976; 1979). The following default values for the geometric sizes of organisms were provided for dose calculation: (1) fish: cylinder 50 cm in length and 10 cm in diameter, g = 41 cm; (2) mollusks: flat cylinder 1 cm in height and 4 cm in diameter, g = 10 cm; (3) algae *Cladophora*: flat layer of 2 cm thickness. Specific geometric factors for cooling pond biota are as follows: bream 1 y of age, g = 23 cm; bream 5 y of age, g = 51 cm; pike-perch 1 y of age, g = 31 cm; pike-perch 5 y of age, g = 75 cm; adult silver carp, g = 94 cm.

For the calculation of external exposure, two cases were considered: (1) the fish spends most of the time (>70%) in water away from the bottom (for example, silver carp); (2) the fish usually resides close to the bottom (for example, bream).

Radioactive Contamination of the Cooling Pond

The reactor of Unit 4 of the Chernobyl NPP, an RBMK-1000 reactor, was put into operation in December 1983. At the time of the accident, 26 April 1986, it had been in service for 865 days. At this time, the reactor core had 1659 fuel assemblies, one additional absorber, and one unloaded channel. Most of the assemblies were fuel assemblies from the first loading with a burn-up of 12-14 MW day kg^{-1}. Each fuel assembly carried 0.1147 metric tons of uranium, the total mass of fuel in the core being 190.2 metric tons (Borovoy et al., 1990).

Primary contamination of the cooling pond as a result of the Chernobyl accident was due mainly to atmospheric fallout from 26 April through May of 1986. The total release of fission products (excluding inert radioactive gases) was estimated to be 1.85 x 10^{18} Bq, which was about 4% of the total activity in the reactor. (The data are decay-corrected to 26 April 1986.) Estimates of the radionuclides released from the damaged reactor are presented in Table 8. The forms of initial fallout in the near zone were as follows: fuel components (non-exchangeable forms), 90-98%, and aerosols, 2-10%. Estimates of the amounts of different radionuclides in the Chernobyl cooling pond (decay-corrected to 30 May 1986) are given in Table 9**.** These estimates were made from sampling data of the radioactive contamination of water and bottom sediments (Kryshev, 1995).

The cooling pond can be considered in terms of three subareas (CP1, CP2, CP3) that differ substantially in the amount of bottom sediment contamination (Figure 1; Table 10). The most contaminated area is the northern part. The activity of bottom sediments was substantially lower in the southern part of the cooling pond (Chernobyl Symposium, 1989). Such drastic differences in the bottom sediment contamination are associated with lack of homogeneity of the ^{137}Cs deposition from the atmosphere, with a maximum occurring in the northern part of the cooling pond. The dynamics of ^{137}Cs in the water of the Pripyat River are presented in Table 11.

EXPERIMENTAL DETAILS

Sampling of water and sediment was performed by standard methods recommended by the State Committee for Hydrometeorology and Monitoring of the Natural Environment of the former USSR (Vakulovsky, 1986). As a rule, water and sediments were collected at the same time and place as biota collections. Collected samples of aquatic organisms were rinsed to remove particles on surfaces and incinerated at a temperature of no more than 350^o C.

The activities of gamma-emitting nuclides were determined by standard gamma-spectrometric methods with a semiconductor gamma spectrometer based on germanium-lithium detectors and multichannel amplitude analyzers (Vakulovsky, 1986). Measurements of ^{137}Cs taken in the laboratories were subjected to intercalibration within the framework of the International Chernobyl Project. The activity of ^{90}Sr was determined by radiochemical methods and from measurement of its decay product, ^{90}Y.

The numbers of measured samples included in the database were as follows: water, 174 samples; bottom sediments, 318; algae, 66; mollusks, 36; and fish, 939. Special attention was given to investigations of the radionuclide content in various species of fish. The activity of ^{137}Cs was measured both in whole fish and in various fish organs, including muscle.

TEST DATA AVAILABLE

1. Concentrations of ^{137}Cs in the following components of the aquatic ecosystem for specified time periods.
    (a) Water (Bq L^{-1}) for each month (monthly mean) from May to December 1986 and for each year (annual mean) from 1987 to 1990, for each region of the cooling pond (CP1, CP2, CP3) and for the entire cooling pond (Table 12).
    (b) Bottom sediment layers (kBq kg^{-1} wet weight, for 0-4, 4-8, 8-12, and 12-20 cm) for July of the years 1986, 1988, and 1990, for each region of the cooling pond (CP1, CP2, CP3) and for the entire cooling pond (Table 13).
    (c) Fish flesh (muscle) (kBq kg^{-1} wet weight) for the years 1986, 1987, 1988, 1989, and 1990 (annual means) (Table 14).
    (d) Fish flesh (muscle) (kBq kg^{-1} wet weight) for predator and nonpredator species for years 1986, 1987, 1988, 1989, and 1990 (annual means) (Table 15).
    (e) Fish flesh (muscle) (kBq kg^{-1} wet weight) for predator and nonpredator species of different age classes for the years 1986, 1987, 1988, 1989, and 1990 (annual means) (Table 16).

2. Concentrations of other radionuclides in bottom sediments and biota of the cooling pond (Tables 17-20).

3. Estimates of dose and risk based on measurements.
    (a) Internal and external dose rates (Gy y^{-1}) from all accident-derived radionuclides for three species of adult fish (bream, pike-perch, silver carp) for the years 1986 to 1995 (Table 21).
    (b) Total accumulated dose (Gy) for fish (bream, pike-perch, silver carp) for the time periods 1986 and 1986 to 1990. Contributions from internal and external pathways of exposure are indicated, as well as the contributions from the two radionuclides of most significance to the total dose for each species (Table 22).
    (c) Absorbed radiation dose (Gy) received by fish (bream, pike-perch, silver carp) of different ages (Table 23).
    (d) Dose rates (Gy y^{-1}) to mollusks (Table 24) and algae (Table 25) in the years 1986, 1987, 1988, 1989, 1990, and 1995.
    (e) Estimated dose (Table 26) and lifetime risk (Table 27) of cancer morbidity to an adult from consumption of 1 kg of fish muscle from the cooling pond in the years 1986 and 1987.

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REFERENCES

BIOMOVS II. 1996. Assessment of the Consequences of the Radioactive Contamination of Aquatic Media and Biota: Model Testing Using Chernobyl Data. Stockholm, Swedish Radiation Protection Institute, BIOMOVS II Technical Report No. 10.

Borovoy, A. A., Ibragimov, G. D., and Ogorodnik, S. S. 1990. The state of the Chernobyl NPP unit and nuclear fuel in it. Chernobyl, The Expedition of Kurchatov's Institute of Atomic Energy (in Russian).

Buzulukov, Yu. P., and Dobrynin, Yu. L., 1993. Release of radionuclides during the Chernobyl accident. In: Merwin, S. E., and Balonov, M. I. (Eds.). The Chernobyl Papers. Vol. I: Doses to the Soviet Population and Early Health Effects Studies. Richland, Washington, Research Enterprises, pp. 3-22.

Chernobyl Symposium, 1988, 1989. Vol. 1, 5, 6. Chernobyl (in Russian).

Hoffman, F. O., Thiessen, K. M., and Watkins, B. 1996. Opportunities for the testing of environmental transport models using data obtained following the Chernobyl accident. *Health Physics* 70:5-7.

Kaftannikova, O. G., Protasov, A. A., Sergeeva, O. A., Kalinichenko, R. A., Vinogradskaya, T. A., Lenchina, L. G., Kosheleva, S. I., Novikov, B. I., Afanasiev, S. A., Sinitsina, O. O., Movchan, N. B., and Pankov, N. G. 1987. The ecology of an NPP's cooling pond. Kiev, Ukraine Academy of Sciences (in Russian).

Kryshev, I. I. (Ed). 1992. Radioecological consequences of the Chernobyl accident. Moscow, Nuclear Society International.

Kryshev, I. I. 1995. Radioactive contamination of aquatic ecosystems following the Chernobyl accident. *Journal of Environmental Radioactivity* 27:207-219.

Kryshev, I. I., and Sazykina, T. G. 1986. Mathematical modelling of radionuclide migration in aquatic ecosystems. Moscow, Energoatomizdat (in Russian).

Kryshev, I. I., Sazykina, T. G., Ryabov, I. N., Chumak, V. K., and Zarubin, O.L. 1996. Model testing using Chernobyl data: II. Assessment of the consequences of the radioactive contamination of the Chernobyl Nuclear Power Plant cooling pond. *Health Physics* 70(1):13-17.

Kryshev, I. I., Sazykina, T. G., Hoffman, F. O., Thiessen, K. M., Blaylock, B. G., Feng, Y., Galeriu, D., Heling, R., Kryshev, A. I., Kononovich, A. L., and Watkins, B. 1999. Assessment of the consequences of the radioactive contamination of aquatic media and biota for the Chernobyl NPP cooling pond: Model testing using Chernobyl data. *Journal of Environmental Radioactivity* 42:143-156.

Protasov, A. A., Sergeeva, O. A., Kosheleva, S. I., Kaftannikova, O. G., Lenchina, L. G., Kalinichenko, R. A., Vinogradskaya, T. A., Novikov, B. I., Afanasiev, S. A., and Sinitsina, O. O. 1991. Hydrobiology of cooling ponds of thermal and nuclear power plants in Ukraine. Kiev, Naukova Dumka (in Russian).

Vakulovsky, S. M. 1986. Methodical recommendations for determining radioactive contamination of aquatic samples. Moscow, Gidrometeoizdat (in Russian).

Woodhead, D. S. 1976. Concentrations of radionuclides in aquatic environments and the resultant radiation dose rates received by aquatic organisms. In: *Effect of ionizing radiation dose rates received by aquatic organisms and ecosystems.* Vienna: International Atomic Energy Agency, Technical Report No. 172, pp. 5-54.

Woodhead, D. S. 1979. Methods of Dosimetry for Aquatic Organisms. In: *Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems*. Vienna: International Atomic Energy Agency, Technical Report No. 190, pp. 43-96.

TABLES OF INPUT DATA

Table 1. Morphometric characteristics of the Chernobyl NPP cooling pond.

Characteristic	Value
Volume (m^3)	1.5×10^8
Area (km^2)	22
Length (km)	11.4
Width, average (km)	2.0
Depth, maximum (m)	20
Depth, average (m)	6.6

Table 2. Characteristics of the cooling pond bottom sediments.

Type of bottom sediment	Area (km^2)	Density (g cm^{-3})
Loamy sand and loam	9.0	1.1 - 1.5
Sand and silted sand	7.0	1.1 - 1.5
Silt	6.0	0.4 - 0.6
Silt of deep-water pits only, upper 10 cm	-	0.1 - 0.2
Sedimentation	**Depth**	**Rate (cm y^{-1})**
	0 - 10 m	0.4 - 2.0
	10	1.2 - 3.2
	12	1.7 - 5.0
	14	2.3 - 6.9
	16	2.9 - 8.7
	18	3.5 - 10.6
	20	4.1 - 12.4

Table 3. Temperature of water in the cooling pond (natural conditions).

Month	Temperature (°C)	Month	Temperature (°C)
January	0.0	July	21.5 ± 0.7
February	0.1	August	24.5 ± 0.4
March	0.4 ± 0.2	September	15.6 ± 0.8
April	8.1 ± 1.3	October	9.0 ± 2.8
May	14.0 ± 1.6	November	4.3 ± 2.6
June	19.6 ± 1.3	December	0.7 ± 0.6

Note: The temperature of water in the heated zone was higher than the natural temperature by 9.4 ± 1.6 °C.

Table 4. Hydrochemical parameters of the cooling pond.

Parameter	Range	Average
Total ions (mg L^{-1})	250 - 350	300
Total hardness (mg L^{-1})	2.90 - 4.16	3.5
Sulphates (mg L^{-1})	10 - 53	30
Chlorides (mg L^{-1})	14 - 28	20
pH	6.5 - 8.4	7.5
Iron (mg L^{-1})	0.1 - 1.3	0.5
Ca (mg L^{-1})	40 - 53	43
Mg (mg L^{-1})	5 - 9	7
K (mg L^{-1})	3 - 5	4
Oxygen (mg L^{-1})	1.6 - 16.5	8.0
Mineral phosphorus (mg L^{-1})	0.01 - 0.51	0.06
Organic phosphorus (mg L^{-1})	0.01 - 0.68	0.06
Nitrate (mg L^{-1})	0.05 - 2.34	0.54
Ammonia (mg L^{-1})	0.15 - 3.46	0.9
Organic nitrogen (mg L^{-1})	0.01 - 3.28	1.0

Table 5. Plankton biomass in the cooling pond.

Component of Plankton	Biomass (mg L^{-1}) Range	Annual average
Bacterial plankton	1.4 – 2.6	2.0
Blue-green algae (Cyanophyta)	0.04 – 16.0	3.2
Diatomic Algae (Bacillariaphyta)	0.3 – 9.5	2.6
Green algae (Chlorophyta)	0.2 – 3.6	0.5
Total phytoplankton	1 - 18	6.6
Zooplankton	0.1 – 9.2	1.8

Table 6. Pre-Chernobyl ^{137}Cs concentrations in components of the cooling pond ecosystem (1985).

Component of ecosystem	^{137}Cs concentration (Bq kg^{-1} wet weight)
Water (Bq L^{-1})	0.013
Bottom sediments:	
silts	140
silted sand	20
loamy sand	26
Mollusks	2
Algae	1
Fish:	
Pike-perch	30
Bream	9

Table 7. Annual averaged biomass of aquatic organisms in the cooling pond.

Aquatic Organisms	Biomass (metric tons)
Bacterial plankton	300 ± 160
Phytoplankton	1000 ± 600
Zooplankton	270 ± 150
Mollusks	500 ± 200
Zoobenthos	10 ± 5
Phytoperiphyton	7 ± 2
Fish (total)	60 ± 40
Nonpredatory fish	50 ± 32
Predatory fish	10 ± 6

Table 8. Estimates of the radionuclides released from the damaged unit at Chernobyl NPP.

Nuclide	Half-life	1986 Estimate* (Bq)	1993 Estimate** (Bq)
^{85}Kr	10.8 years	3.3×10^{16}	3.3×10^{16}
^{89}Sr	50.5 days	9.3×10^{16}	8.1×10^{16}
^{90}Sr	28.1 years	8.1×10^{15}	8.1×10^{15}
^{95}Zr	64 days	1.6×10^{17}	1.7×10^{17}
^{103}Ru	39.3 days	1.4×10^{17}	1.7×10^{17}
^{106}Ru	368 days	5.9×10^{16}	3.0×10^{16}
^{131}I	8.04 days	6.3×10^{17}	1.7×10^{18}
^{132}Te	3.62 days	4.1×10^{17}	4.1×10^{17}
^{133}Xe	5.27 days	6.3×10^{18}	6.3×10^{18}
^{134}Cs	2.06 years	1.9×10^{16}	4.4×10^{16}
^{137}Cs	30 years	3.7×10^{16}	8.5×10^{16}
^{140}Ba	12.7 days	2.7×10^{17}	1.7×10^{17}
^{141}Ce	32.5 days	1.3×10^{17}	2.0×10^{17}
^{144}Ce	284 days	8.9×10^{16}	1.4×10^{17}
^{238}Pu	87.7 years	3.0×10^{13}	3.0×10^{13}
^{239}Pu	24,000 years	2.6×10^{13}	3.0×10^{13}
^{239}Np	2.36 days	8.5×10^{17}	1.7×10^{18}
^{240}Pu	6540 years	3.7×10^{13}	4.4×10^{13}
^{241}Pu	14.4 years	5.2×10^{15}	5.9×10^{15}
^{242}Pu	376,000 years	7.4×10^{10}	8.5×10^{10}
^{242}Cm	163 days	7.8×10^{14}	9.3×10^{14}

*Data are decay-corrected to April 26, 1986, and are taken from "The accident..." (1986) as reported in Buzulukov and Dobrynin, 1993.

**Data are decay-corrected to April 26, 1986, and are taken from Buzulukov and Dobrynin, 1993.

Table 9. Estimates of amounts of radionuclides in the Chernobyl cooling pond (30 May 1986).

Radionuclide	Sediments, 10^{12} Bq	Water, 10^{12} Bq
^{137}Cs	110 ± 50	60 ± 30
^{134}Cs	60 ± 40	30 ± 15
^{144}Ce	860 ± 400	30 ± 20
^{141}Ce	640 ± 280	50 ± 30
^{106}Ru	220 ± 100	20 ± 10
^{103}Ru	700 ± 360	40 ± 15
^{95}Zr	1200 ± 500	50 ± 30
^{95}Nb	1100 ± 400	70 ± 40
^{140}Ba	400 ± 140	120 ± 70
^{140}La	280 ± 120	80 ± 40
^{131}I	30 ± 10	250 ± 60
^{90}Sr	50 ± 20	6 ± 4

Table 10. Estimated amounts of ^{137}Cs in the upper layer of sediments (0 - 4 cm) of the three subareas of the Chernobyl cooling pond (decay-corrected to 30 May 1986).

	Areas of Cooling Pond		
	CP1	CP2	CP3
Water volume (m^3)	13×10^6	76×10^6	62×10^6
Sediment area (m^2)	2×10^6	11×10^6	9×10^6
Activity of ^{137}Cs (10^{12} Bq)	20 ± 7	85 ± 40	5 ± 3

Table 11. Annual average concentrations of ^{137}Cs in the Pripyat River, Bq L^{-1}.

Year	Solution	Suspension
1986 (May-Dec)	20.6 ± 14.0	1.6 ± 1.0
1987	1.3 ± 0.1	0.5 ± 0.04
1988	0.45 ± 0.1	0.22 ± 0.04
1989	0.25 ± 0.06	0.2 ± 0.03
1990	0.16 ± 0.04	0.1 ± 0.03

TABLES OF TEST DATA

Table 12. ^{137}Cs activity in the cooling pond water, Bq L^{-1}.

	Cooling pond area				
	ECP[a]	CP1	CP2	CP3	Number of samples (ECP)
Monthly means:					
May 1986	400 ± 300[b]	1800 ± 1400	400 ± 150	100 ± 30	17
June 1986	360 ± 210	1500 ± 1100	380 ± 110	100 ± 40	12
July 1986	250 ± 180	640 ± 400	300 ± 160	90 ± 40	8
August 1986	170 ± 100	400 ± 230	200 ± 90	80 ± 40	12
September 1986	150 ± 100	340 ± 210	160 ± 80	90 ± 25	12
October 1986	160 ± 70	400 ± 180	180 ± 80	100 ± 30	10
November 1986	170 ± 70	280 ± 120	200 ± 90	110 ± 35	12
December 1986	120 ± 50	170 ± 80	140 ± 80	80 ± 25	3
Annual means:					
1987	100 ± 60				36
1988	50 ± 20				40
1989	30 ± 14				36
1990	14 ± 6				30

[a] Entire cooling pond
[b] Mean and 95% confidence interval (Tables 10 – 21)

Table 13. ^{137}Cs activity in the profile of the cooling pond sediments, kBq kg^{-1} wet weight.

Location Sediment layer, cm	^{137}Cs activity July 1986	 July 1988	 July 1990
ECP			
0 - 4	170 ± 80	140 ± 90	110 ± 60
4 - 8	<10	40 ± 20	60 ± 40
8 - 12	<10	10 ± 5	13 ± 7
12 - 20	-	-	<5
CP1			
0 - 4	310 ± 120	270 ± 100	200 ± 110
4 - 8	<10	80 ± 30	130 ± 70
8 - 12	<10	<5	30 ± 20
12 - 20	-	<5	<5
CP2			
0 - 4	260 ± 130	200 ± 100	160 ± 90
4 - 8	<10	70 ± 40	100 ± 60
8 - 12	<10	10 ± 5	20 ± 15
12 - 20	-	<5	<5
CP3			
0 - 4	15 ± 10	20 ± 10	16 ± 8
4 - 8	-	-	-
8 - 12	-	-	-
12 - 20	-	-	-

Table 14. ^{137}Cs activity in fish flesh (muscle), kBq kg^{-1} wet weight.

Time	^{137}Cs activity	Number of samples
1986 (May - Dec.)	220 ± 100	140
1987	160 ± 60	218
1988	100 ± 30	197
1989	60 ± 26	84
1990	40 ± 12	300

Table 15. ^{137}Cs Activity in different groups of fish, kBq kg^{-1} wet weight.

Time	^{137}Cs activity	
	Nonpredators	Predators
1986 (May - Dec.)	250 ± 120	110 ± 60
1987	130 ± 50	300 ± 90
1988	60 ± 30	260 ± 100
1989	30 ± 14	180 ± 60
1990	23 ± 11	110 ± 70

Table 16. ^{137}Cs activity in fish of different age classes, kBq kg^{-1} wet weight.

Fish type	Age (year of birth)	Year of measurement 1986	1987	1988	1989	1990
Nonpredators	1986	240 ± 100	130 ± 40	41 ± 6	32 ± 4	19 ± 5
(Bream)	1987		60 ± 25	30 ± 3	18 ± 4	10 ± 3
	1988			22 ± 4	-	8 ± 4
	1989				-	5 ± 1
	1990					5 ± 2
Predators	1986	60 ± 20	320 ± 80	280 ± 60	130 ± 40	120 ± 30
(Pike-perch)	1987		180 ± 40	140 ± 30	120 ± 30	85 ± 22
	1988			90 ± 20	70 ± 25	62 ± 34
	1989				-	40 ± 18
	1990					46 ± 15

Table 17. Radionuclide activities in the upper layer of sediments (0-4 cm) of the cooling pond, kBq kg^{-1} wet weight.

Radionuclide	July 1986	July 1988	July 1990
^{89}Sr	160 ± 80	-	-
^{90}Sr	60 ± 25	50 ± 20	45 ± 20
^{95}Zr	600 ± 250	-	-
^{95}Nb	800 ± 300	-	-
^{103}Ru	220 ± 110	-	-
^{106}Ru	200 ± 100	40 ± 20	8 ± 5
^{134}Cs	80 ± 40	35 ± 20	15 ± 8
^{137}Cs	170 ± 80	140 ± 90	110 ± 60
^{140}Ba	15 ± 5	-	-
^{140}La	12 ± 6	-	-
^{141}Ce	170 ± 70	-	-
^{144}Ce	700 ± 300	110 ± 60	15 ± 10
Number of samples	174	46	18

Table 18. Radionuclide activities in fish (whole body) of the cooling pond, kBq kg^{-1} wet weight.

Radionuclide	1986	1987	1988	1989	1990
Bream					
^{90}Sr	1.0 ± 0.5	2.0 ± 1.0	-	-	-
^{106}Ru	9.0 ± 3.0	3.0 ± 1.0	-	-	-
^{134}Cs	75 ± 30	40 ± 10	8 ± 3	4 ± 2	2 ± 0.6
^{137}Cs	160 ± 70	120 ± 30	30 ± 10	20 ± 8	13 ± 4
^{144}Ce	15 ± 6	7 ± 3	-	-	-
No. of samples	4	54	17	9	16
Pike-perch					
^{90}Sr	1.3 ± 0.8	2.2 ± 1.0	-	-	-
^{134}Cs	50 ± 25	100 ± 35	65 ± 30	30 ± 10	14 ± 9
^{137}Cs	110 ± 60	300 ± 90	260 ± 100	180 ± 60	110 ± 70
No. of samples	3	45	23	5	39
Silver carp					
^{90}Sr	2.0 ± 1.0	2.2 ± 1.0	-	-	-
^{106}Ru	34 ± 20	11 ± 6	2 ± 1	-	-
^{134}Cs	120 ± 60	45 ± 20	15 ± 8	6 ± 3	3 ± 2
^{137}Cs	250 ± 120	130 ± 50	60 ± 30	30 ± 14	23 ± 11
^{144}Ce	40 ± 20	26 ± 14	18 ± 7	2 ± 1	1.4 ± 0.8
No. of samples	3	96	62	46	48

Table 19. Radionuclide activities in the cooling pond mollusks (whole body), kBq kg^{-1} wet weight.

Radionuclide	1986	1987	1988
^{90}Sr	50 ± 10	54 ± 15	70 ± 20
^{95}Zr	26 ± 17	0.3 ± 0.2	-
^{95}Nb	34 ± 18	0.5 ± 0.3	-
^{106}Ru	30 ± 20	8 ± 5	2 ± 1
^{134}Cs	10 ± 3	5 ± 1.4	3 ± 1.5
^{137}Cs	25 ± 6	21 ± 5	14 ± 8
^{144}Ce	110 ± 70	10 ± 6	3 ± 1
Number of samples	9	21	6

Table 20. Radionuclide activities in the cooling pond algae, kBq kg^{-1} wet weight.

Radionuclide	1986	1987	1988	1989	1990
^{90}Sr	15 ± 10	20 ± 14	12 ± 6	-	10 ± 4
^{95}Zr	100 ± 70	40 ± 26	3 ± 2	-	-
^{95}Nb	200 ± 130	74 ± 40	5 ± 3	-	-
^{106}Ru	80 ± 60	60 ± 40	16 ± 10	6 ± 3	4 ± 2
^{134}Cs	40 ± 15	21 ± 30	11 ± 5	8 ± 3	4 ± 1.5
^{137}Cs	120 ± 40	60 ± 30	40 ± 20	40 ± 12	24 ± 7
^{144}Ce	320 ± 200	200 ± 140	86 ± 50	86 ± 50	9 ± 6
No. of samples	7	28	5	6	20

Table 21. Internal and external dose rates for fish, Gy y^{-1}.

Fish	Year	Internal irradiation	External irradiation	Total
Bream	1986	0.30 ± 0.20	1.8 ± 1.3	2.1 ± 1.5
	1987	0.27 ± 0.17	0.8 ± 0.5	1.1 ± 0.7
	1988	0.094 ± 0.06	0.54 ± 0.34	0.63 ± 0.40
	1989	0.05 ± 0.03	0.36 ± 0.22	0.41 ± 0.25
	1990	0.04 ± 0.024	0.24 ± 0.14	0.28 ± 0.17
	1995	0.02 ± 0.012	0.18 ± 0.09	0.20 ± 0.10
Pike-perch	1986	0.11 ± 0.08	0.90 ± 0.63	1.0 ± 0.7
	1987	0.50 ± 0.34	0.40 ± 0.27	0.9 ± 0.6
	1988	0.40 ± 0.25	0.27 ± 0.18	0.67 ± 0.43
	1989	0.26 ± 0.15	0.18 ± 0.12	0.44 ± 0.27
	1990	0.14 ± 0.08	0.12 ± 0.07	0.26 ± 0.15
	1995	0.08 ± 0.05	0.09 ± 0.06	0.17 ± 0.11
Silver carp	1986	0.50 ± 040	0.30 ± 0.20	0.8 ± 0.6
	1987	0.33 ± 023	0.13 ± 0.09	0.46 ± 0.32
	1988	0.23 ± 0.15	0.09 ± 0.06	0.32 ± 0.21
	1989	0.07 ± 0.04	0.06 ± 0.04	0.13 ± 0.08
	1990	0.05 ± 0.03	0.04 ± 0.03	0.90 ± 0.06
	1995	0.04 ± 0.02	0.03 ± 0.02	0.07 ± 0.04

Table 22. Total dose to fish in the cooling pond, Gy.

Time period	Species of fish		Dose
	BREAM		
1986	total:		2.1 ± 1.5
		external	1.8
		internal	0.3
		^{144}Ce	1.2
		^{95}Zr	0.4
1986-1990	total:		4.5 ± 3.0
		external	3.7
		internal	0.8
		^{144}Ce	1.8
		^{137}Cs	1.0
	PIKE-PERCH		
1986	total:		1.0 ± 0.7
		external	0.9
		internal	0.1
		^{144}Ce	0.6
		^{95}Zr	0.2
1986-1990	total:		3.3 ± 2.2
		external	1.9
		internal	1.4
		^{137}Cs	1.5
		^{144}Ce	0.9
	SILVER CARP		
1986	total:		0.8 ± 0.6
		external	0.3
		internal	0.5
		^{137}Cs	0.27
		^{144}Ce	0.25
1986-1990	total:		1.8 ± 1.3
		external	0.6
		internal	1.2
		^{137}Cs	0.7
		^{144}Ce	0.6

Table 23. Absorbed radiation dose for fish of different ages, Gy.

Fish	Age	Dose				
	(Year of birth)	1986	1987	1988	1989	1990
Bream	1986	2.1 ± 1.5	3.2 ± 2.2	3.8 ± 2.6	4.2 ± 2.9	4.5 ± 3.0
	1987		1.1 ± 0.7	1.7 ± 1.1	2.1 ± 1.4	2.4 ± 1.6
	1988			0.6 ± 0.4	1.0 ± 0.7	1.3 ± 0.9
	1989				0.4 ± 0.2	0.7 ± 0.4
	1990					0.3 ± 0.2
Pike-perch	1986	1.0 ± 0.7	1.9 ± 1.3	2.6 ± 1.7	3.0 ± 2.0	3.3 ± 2.2
	1987		0.9 ± 0.6	1.6 ± 1.0	2.1 ± 1.3	2.4 ± 1.5
	1988			0.7 ± 0.4	1.1 ± 0.7	1.4 ± 0.9
	1989				0.4 ± 0.3	0.7 ± 0.5
	1990					0.3 ± 0.2
Silver carp	1986	0.8 ± 0.6	1.3 ± 0.9	1.6 ± 1.1	1.8 ± 1.2	1.9 ± 1.3
	1987		0.5 ± 0.3	0.8 ± 0.5	0.9 ± 0.6	1.0 ± 0.7
	1988			0.3 ± 0.2	0.5 ± 0.3	0.6 ± 0.4
	1989				0.13	0.24
	1990					0.09

Table 24. Dose rates for mollusks, Gy y^{-1}.

Year	Internal irradiation	External irradiation	Total
1986	0.70 ± 0.50	3.0 ± 2.1	3.7 ± 2.6
1987	0.46 ± 0.30	1.3 ± 0.9	1.8 ± 1.2
1988	0.45 ± 0.30	0.9 ± 0.6	1.4 ± 0.9
1989	0.35 ± 0.21	0.6 ± 0.4	1.0 ± 0.6
1990	0.30 ± 0.16	0.40 ± 0.23	0.7 ± 0.4
1995	0.20 ± 0.12	0.30 ± 0.19	0.5 ± 0.3

Table 25. Dose rates for algae, Gy y^{-1}.

Year	Internal irradiation	External irradiation	Total
1986	1.4 ± 1.1	2.4 ± 1.9	3.8 ± 3.0
1987	1.7 ± 1.2	1.0 ± 0.7	2.7 ± 1.9
1988	0.65 ± 0.40	0.7 ± 0.5	1.4 ± 0.9
1989	0.60 ± 0.33	0.50 ± 0.28	1.1 ± 0.6
1990	0.15 ± 0.10	0.30 ± 0.20	0.45 ± 0.30
1995	0.06 ± 0.03	0.24 ± 0.13	0.30 ± 0.16

Table 26. Estimated dose from consumption of 1 kg of cooling pond fish, mSv.

Year	Mean	95% confidence interval (about the arithmetic mean)	
		lower bound	upper bound
1986	5.6	2.5	8.7
1987	3.5	1.3	5.7

Table 27. Estimated lifetime risk of cancer morbidity to an adult human from consumption of 1 kg of cooling pond fish.

Year	Mean	95% confidence interval (about the arithmetic mean)	
		lower bound	upper bound
1986	4.1×10^{-4}	1.8×10^{-4}	6.4×10^{-4}
1987	2.6×10^{-4}	9.5×10^{-5}	4.2×10^{-4}

Figure 1. The Chernobyl NPP cooling pond. The three areas (CP1, CP2, CP3) represent different levels of bottom sediment contamination as described in Table 10.